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Ice formation is removed by inducing mechanical vibrations in the audible range of frequencies, where the mechanical vibrations are of an amplitude sufficient to cause ice-expelling strain deformation.

ABSTRACT

Ice formation is removed by inducing mechanical vibrations in the audible range of frequencies, where the mechanical vibrations are of an amplitude sufficient to cause ice-expelling strain deformation.

DE-ICING SYSTEM AND METHOD

FIELD

[0001] The invention relates to deicing with mechanical deformation (vibrations).

BACKGROUND

[0002] Ice accumulations can form on structures from a number of sources. These include glaze from precipitating freezing rain or freezing drizzle, rime ice resulting from supercooled cloud or fog droplets. Ice can also be formed from sea spray for instance. Ice often accumulates on horizontal surfaces but can also accumulate on vertical surfaces, especially those facing the wind.

[0003] There are several applications where accumulations of ice are particularly undesirable. Aircraft components is one of these, in particular when considering airfoils e.g. plane wings, propeller blades, helicopter rotor blades etc. given the effect ice accumulations can have on the aerodynamic characteristics of such components or other critical components such as air inlets. Another example is the field of offshore platforms used in arctic climates where superstructure ice can reduce rig stability, damage rig structure due to changes in stress on structural components, cause slipping hazards, render deck cargo unavailable, disable winches, cranes, railings, cables, and antennas, cover windows, rescue equipment, hatches, firefighting equipment, valves, radomes, air intakes. The accumulation of ice on safety equipment can be highly problematic, especially in the event of an emergency.

[0004] There are several known approaches for de-icing, ranging from hitting the ice with a baseball bat to using heat, for instance. Nonetheless, there remained room for improvement.

SUMMARY

[0006] It was found that a de-icing effect can be obtained by inducing vibratory deformations in the audible range of frequencies, where the amplitude of the deformation is sufficient.

[0007] In accordance with one aspect, there is provided a de-icing device for a substructure, the de-icing device comprising : a protection sheet having a shape matching a shape of the substructure, the protection sheet being made integral to the substructure with a spacing being located between the protection sheet and the substructure, the protection sheet having an ice accumulation surface facing away from the substructure, and an underface surface facing the substructure; and at least one piezoelectric transducer positioned within the spacing and being securely bounded to the underface surface of the protection sheet, said at least one piezoelectric transducer being operable to impart vibrations at frequencies in the audible range, wherein said vibrations are of an amplitude producing a sufficient deformation in the protection sheet to remove ice accumulated thereon.

[0008] In accordance with one aspect, there is provided a method of removing ice accumulation on a sheet material, the method comprising inducing vibrations in the sheet material, the vibrations being in the audible range of frequencies and being of an amplitude sufficient to cause deformations of above 50 $\mu\xi$ in the sheet material.

[0009] For reference, the audible range of sound vibrations (or sonic vibrations) for humans is generally recognized as spanning between the frequencies of 20 Hz and 20 000Hz (20kHz). This definition is used herein.

DESCRIPTION OF THE DRAWINGS

[0010] Fig. 1 is a cross-sectional view of a first embodiment of a de-icing device;

[0011] Fig. 2 is an elevation view of the de-icing device of Fig. 1;

[0012] Fig. 3A, 3B, 3C are an elevation view, an enlarged and fragmented elevation view, and a cross-sectional view of a second embodiment of a de-icing device;

[0013] Fig. 4 is a cross-sectional view of a third embodiment of a de-icing device;

[0014] Fig. 5 is a perspective view of a fourth embodiment of a de-icing device; and

[0015] Fig. 6 is a block diagram showing an embodiment of a controller for a de-icing device.

DETAILED DESCRIPTION

[0016] Fig. 1 shows a cross-section of a first example of a de-icing device 10. The de-icing device 10 can be seen to generally include a protection sheet 16 which is made integral to a substructure 14 it protects from ice. The protection sheet 16 has an outer surface referred to herein as the ice accumulation surface 20, facing away from the substructure and being exposed to ice formation, and an opposite underface surface 22 which faces the substructure. The protection sheet 16 is made integral to the substructure 14 in a manner to leave a spacing 24 between the inner surface 22 of the sheet 16 and the substructure 14. An actuator, such as a piezoelectric transducer 26 is bound to the underface surface 22 of the protection sheet 16. As will be detailed below, the actuator can be operated to make the protection sheet 16 vibrate at frequencies in the audible range (i.e. between 20 Hz and 20,000 Hz, preferably between 1 and 10 kHz) and at a sufficient amplitude (typically above 50 µξ, preferably above 150 µξ) to break off and expulse ice formed on the ice accumulation surface 20. A role of the spacing 24 is to provide clearance between the protection sheet 16 and the substructure 14 for the protection sheet 16 to be free to vibrate.

[0017] The protection sheet 16 should provide a sufficient robustness/rigidity to be durable in view of its intended application and effectively protect the substructure, and allow vibrations imparted by the actuator to travel across a satisfactory surface area. However, at the same time, it needs to be elastic to a sufficient extend to allow the deformation within the required amplitudes to remain in the elastic domain of deformation. To this end, a metal sheet can be used, for instance. A material such as aluminium can be preferable to a material such as titanium, for instance, because aluminium has an elastic modulus (Young's modulus) which is significantly lower than that of titanium, and may thus require less power to deform to the desired extend within the elastic domain of deformation.

[0018] The protection sheet 16 can be made integral to the substructure 14 in any suitable manner. In the specific embodiment illustrated in Fig. 1, the protection sheet 16 is made integral to the substructure 14 by way of fastening, more specifically : a plurality fasteners 18 can be used along two opposite edges 28, 30 of the protection sheet 16 to secure the protection sheet 16 to the substructure 14, in which case the spacing 24 can be empty (i.e. filled with air) and be provided by way of a corresponding plurality of spacers 32. In an alternate embodiment, a layer of vibration-permeable filler material can be provided in the spacing, in which case the fasteners can be omitted if the adherence of the vibration-permeable filler material layer to the substrate and the protection sheet is considered to provide satisfactory robustness, for instance.

[0019] In the specific example of a protection sheet 16 made of aluminium fastened to the substructure via spacers and having an empty spacing, a deformation amplitude above 150 $\mu\xi$, preferably above 200 $\mu\xi$, has been shown to provide satisfactory ice expulsion characteristics for certain applications, in which case a spacing in the order of 2 mm can be satisfactory for instance. In a specific example of a protection sheet 16 made of aluminium and having a dimension of 0.2 m X 0.2 m, to which a P-876 Dura-Act^{TM} piezoelectric transducer of the model P-876.A15, manufactured by PI, positioned at the center of the protection sheet such as illustrated in Fig. 2, it can be calculated that operating the piezoelectric transducer at 500V during a frequency sweep between 1 and 10 kHz can induce ripple-like strain in the protection sheet to a deformation in the order of $300 \pm 100\ \mu\xi$. The power in this case can be considered of 0.9 to 9 kW/m^2.

[0020] It is noted that the rigidity of the protection sheet 16 may be tailored by varying its thickness or by choosing material with varied ductility and/or hardness. A Young modulus that is similar to or higher than that of ice is typically suitable.

[0021] Tests with a 1mm thickness flat aluminium plate set-up using a thick stack model number Qp20n manufactured by MIDE consisting of two layers of PZT-5 wafers 0.25 mm thick totalling 0.5 mm of piezo material thickness, having surface area dimensions of 46.0 mm X 20.6 mm have shown satisfactory de-icing upon operating the piezos at full rated voltage of 400 Vpp for a circular patch of -15 °C rime ice having 20mm radius and 8mm thickness and for a circular patch of -10° C glaze ice having 35 mm radius and 7mm thickness. The first deicing occurred during a slow, 300 second, logarithmic frequency sweep from 1 to 2 kHz. A faster cyclic sweep, called Frequency Modulation (FM), from 1 to 2 kHz and back at a 1 Hz rate was also able to deice. The FM sweep reduced deicing time down to 21 seconds. Partial deicing was also achieved by driving 25 mm x 25 mm PZT-5 0.8 mm thick piezo wafers manufactured by Sensor Tech.

[0022] For the piezoelectric transducers 26 to be efficient at generating vibration of the sheet 16 at effective de-icing mode frequencies, the selection of the piezoelectric transducers should consider their material and their thickness. The piezoelectric material should have a high coupling factor, which is highly affected by the quality of the bond/contact with the protection sheet, and a high charge constant in order to produce large amplitude vibrations and high strains at effective de-icing mode frequencies. In this view, if the protection sheet is curved, the piezoelectric transducer should correspondingly be curved and/or be positioned in a region of the protection sheet which has a lesser degree of curvature. The loss coefficient should also be minimized to reduce the conversion of electrical energy into heat which may create localized melting of ice at and around the actuators 26. Lead zirconate titanate piezoelectric materials known in the field as PZT-5 can offer a good balance of effective factors. The thickness of the piezoelectric transducers 26 across the electrodes should be balanced with the capabilities of the electrical system. A thicker piezoelectric transducer 26 generates more force for actuating the vibration of the sheet 16, which, in turn, can provide a more effective de-icing. However, increasing the thickness of the piezoelectric transducer 26 typically increases the voltage requirement to achieve the required displacement. In one embodiment, the required actuation voltage level is reduced by the stacking piezoelectric devices in each piezoelectric transducer 26. Large vehicles or structural applications which have more available power may use thicker piezoelectric devices or larger piezoelectric stacks to create a more robust de-icing system while more optimization may be required on the piezoelectric transducer thickness and sheet material and thickness for small vehicles and applications with power restrictions.

[0023] The importance of the driving signal in piezo ice protection cannot be under stated. Literature research indicated that effective icing frequencies would be in the higher supersonic ranges. At these ranges the ability to apply high voltage across the piezos was limited by the current requirements. The higher frequencies effectively increase the required power for driving piezos exponentially as frequency increased. The application of sonic frequencies kept power levels at acceptable levels while allowing complex modal responses to occur and provide sufficient strains. The frequency sweep was introduced to cover the change in effective frequency which would occur due to the high variation in ice deposits. Sweeping also allowed to obtain two effective modal responses activated for more robust icing and straining of the entire surface. Once it was determined that sonic frequencies between 1 and 10 kHz were effective the circuit selection could be tailored to fit the piezo driving conditions. Once the effective range is determined it can be focused down to a few thousand Hertz. The reduction of the bandwidth size gives more time for resonating at the effective modes. This can also be achieved by slowing the frequency sweep but this would increase the on time and power requirements. Small bandwidth sweeps of a few kHz can be driven in cycles shorter than 1 second shrinking the total on time of the system to protect a given area. The selection and shrinking of the band width will be different for each overall system. Therefore a piezo ice protection system can require tuning to the effective frequency of each specific application and then applied to all cases.

[0024] As shown in Fig. 2, a plurality of de-icing devices 10 can be adjoined to cover a substructure. This can be useful in covering a wall, post, or other vertical surface substructure of an offshore platform intended for use in arctic climates, for instance. In the embodiment shown in Fig. 2, there is only a single piezoelectric transducer for each de-icing device 10, but it will be understood that in alternate embodiments, a single de-icing device can cover a greater area and be provided with more than one piezoelectric transducer to propagate a suitable degree of vibrations across the entire area, in which case the piezoelectric transducers can be operable sequentially and/or collectively, for instance.

[0025] Figs 3A to 3C illustrate another embodiment of a de-icing device 110 shown applied to a security door 112 of an offshore platform. In this embodiment, the de-icing device 110 can be used to automatically remove peripheral ice deposits on the security door 112 to allow its use in case of an emergency, for example. The peripheral portion of the security door 112 therefore forms the substructure 114 in this case. The protection sheet 116 can be formed to match the shape of the substructure 114. To this end, the protection sheet 116 can have a folded configuration at an outer edge 128 in order to snugly abut against a rubber bushing 134 provided along a frame structure 136. The protection sheet 116 can be made integral to the substructure 114 by way of fasteners 118 for instance which can also serve in maintaining a satisfactory spacing 124 for the vibrations to occur. A plurality of piezoelectric transducers 126 can be interspaced across the surface of the protection sheet 116 in an amount sufficient for the vibrations to propagate satisfactorily.

[0026] Fig. 4 shows still another embodiment of a de-icing device 210 where the substructure is a portion of an airfoil 214. The airfoil 214 can be a main rotor blade for a helicopter for instance, with the substructure being the leading edge thereof – a portion particularly subject to ice formation, for instance. It is to be noted that Fig. 4 is schematized and that the de-icing device 210 can be recessed in order to form a continuous surface with the adjacent outer surface of the airfoil 214.

[0027] In this embodiment, the protection sheet 216 is curved to match the underlying shape of the substructure that it covers. Although only a cross-section is shown in Fig. 4, it is to be understood that the de-icing device 210 can extend along the length of the airfoil 214, with a plurality of piezoelectric transducers 226 interspaced along the length of the airfoil 214. The curved configuration of the protection sheet 216 in this embodiment creates certain design requirements. The available piezoelectric transducer 226 satisfying other design requirements can have a limited amount of flexibility. In turn, lack of flexibility can affect the bond between piezoelectric transducer 226 and the protection sheet 216, and thereby negatively affect the amount of transmitted mechanical vibrational power therebetween, posing increased actuator power requirements for a given amount of ice-expulsing mechanical deformation. This inconvenience can be addressed by selecting piezoelectric transducers 226 having greater flexibility, and by positioning the piezoelectric transducers 226 at satisfactory areas of the protection sheet where the curvature is minimal. In the illustrated embodiment, this was achieved by positioning the piezoelectric transducers 226 in the areas having a lesser degree of curvature above and below the airfoil 214, adjacent the edges 228, 230 and away from the highly curved leading edge 238. PI P876.A15 piezoelectric transducers referred to above were also found more flexible (bendable) than the MIDE piezoelectric transducers referred to above and were therefore found more satisfactory at similar electric field conditions. This allowed obtaining a better bond between the piezoelectric transducers 226 and the protection sheet 216 and a better mechanical transmission of the vibrations.

[0028] In this embodiment, a layer of vibration-permeable filler material 240 in the spacing 224. A characteristic which is sought from this material is for it to be vibration-permeable in the sense that it favours a higher degree of deformation from the mechanical vibrations induced by the piezoelectric transducers, i.e. it aims to minimally impede the deformation. Elastomers, such as rubber or polyurethane, can be satisfactory vibration-permeable filler materials in certain applications.

[0029] Further, in this embodiment, the layer of vibration-permeable filler material 240 is securely bonded to both the protection sheet 216 and the substructure 214. In certain conditions, the integrity of the bond so formed between the protection sheet 216 and the substructure 214 can be satisfactory to make them integral to an extent where fasteners can be omitted. In an alternate embodiment, fasteners can be used and the layer of vibration-permeable filler material 240 be omitted, for instance, and in yet another embodiment, the layer of vibration-permeable filler material 40 can be bonded to a substructure which is removable from the airfoil 214 for service of the de-icing device, for instance, or for removal when flying in non-icing conditions.

[0030] In the illustrated embodiment, the vibration-permeable filler material 240 can completely fill the spacing 224 between the protection sheet 216 and the underlying substructure with the exception of apertures 242 which can be formed to accommodate the piezoelectric transducers 26 such that an aperture 242 remains between each piezoelectric transducer 26 and the substructure such that the actuators 26. In some embodiments, the apertures 242 can be configures in a manner to allow evacuation of heat generated by the piezoelectric transducers 226.

[0031] It will be noted that in alternate embodiments, an anti-icing coating can optionally be applied to the ice accumulation surface 244 of the protection sheet 216 impede icing and ease de-icing. Depending of application needs, suitable coatings may include low adhesion coatings such as Wearlon®, nanostructured superhydrophobic coatings and chemically semi-active coatings such as Phasebreak™. In still an alternate embodiment, the edges 228, 230 of the protection sheet 216 can be curved inwardly so as to form a hook-like hem (not shown) which can used to form the spacing 224.

[0032] In accordance with one specific design example, the protection sheet 216 is a sheet of aluminum having a thickness of 0.5 mm. The protection sheet 216 is shaped to conform to the shape of the profile of the leading edge portion of the airfoil 214 such that it covers the ice prone area thereof. The protection sheet 216 covers the upper and the lower surface from the leading edge portion 238 back to 20 % of the total chord length. The layer of vibration-permeable filler material 240 is a 1 mm thick layer of supple rubber. A plurality of piezoelectric transducers 226 are bonded on the inside surface of the protection sheet 216 at evenly spaced intervals of 200 mm as far away from the leading edge portion 238 as possible on both the upper and lower surfaces. PZT-5 piezoelectric wafers with dimensions of 50 mm x 30 mm and a thickness of 0.5 mm are used as the piezoelectric transducers 226. In this case, the frequency of the driving signals sweeps from 1 kHz to 10 kHz at a sweep rate of 1 Hz. In such an example embodiment, strain amplitudes of up to 0.0005 are produced within the protection sheet 216 at effective de-icing frequencies within the sweep range, which is typically sufficient to achieve effective de-icing.

[0033] Testing two different airfoil types led to discover that the modal responses were different for each prototype. For instance, sweeping from 1 to 10 kHz allowed to show that according to a first, thicker airfoil type, the highest deformations and ice expulsion were obtained when sweeping between 1 and 4 kHz, whereas according to a second, thinner airfoil type, the highest deformations and ice expulsion were obtained when sweeping between 3 and 6 kHz. Once the modal response of a specific application are determined, the sweeping bandwidth can be narrowed to reduce power consumption or increase de-icing speed.

[0034] Fig. 5 shows still another embodiment of a de-icing device 310. In this configuration, a plurality of plates 316 having a long and narrow configuration are used as fins in a mesh structure 350 which is subject to icing. This structure can be an air inlet or a flooring, for instance. The plates 316 can be secured at both ends to a frame 348 or other structure and can each have a corresponding piezoelectric transducer 326 to induce de-icing vibrations therein at acoustic frequencies and de-icing amplitudes. Transversal plates 352 shown herein are optional. If both transversal and longitudinal plates 316 are used, they can be left free from one another at the nodes 354 such as by using mating slit configurations for instance, in order to facilitate the propagation of the vibrations from the corresponding piezoelectric transducers 326 along the entire length of the plates 316. In alternate embodiments, it will be understood that the vibrations can come from other sources than piezoelectric transducers 326.

[0035] Fig. 6 shows an example of a controller 60 for generating the drive signals to drive the actuators. In this example, the controller 60 has a function generator 62 for generating the alternative signal of various frequencies used to drive the actuators, a power amplifier 64 to amplify the alternative signal to the required power and an output transformer 64 to multiply the voltage of the amplified alternative signal and generate the drive signals for the actuators. In one embodiment, the function generator 62 can have a function generator of the model 33220A by AGILENT, the power amplifier 64 can have an amplifier of the model AL-1000-HF-A by AMP-LINE and the output transformer 64 can be a 14:1 transformer including a power source of the model AL-100DC by AMP-LINE for offsetting the signal, for instance.

[0036] The function generator 62 is capable of generating proper alternative voltages with the frequencies in the acoustic ranges and can include a frequency modulator providing a frequency sweeping mode for sweeping the frequency of the drive signals in a given manner along a given sweeping bandwidth.

[0037] Alternate embodiments can be used to satisfy voltage amplitude requirements to obtain the required strain amplitude at the de-icing frequency modes.

[0038] It is noted that the effective de-icing mode frequencies vary with the configuration of the sleeve and with the various effects of ice accretion on the sleeve. The frequency sweep range is thus typically chosen so as to cover the variation range of the effective de-icing modes. The effective de-icing mode frequencies are those which are shown to be effective on testing. Modal or de-icing tests are generally performed on the sleeve in operation before mass production. The effective de-icing modes are generally those past the first two vibration modes since complex modal motions that include all three surface movements of bending, extension and torsion are more effective at de-icing. The effective frequencies for the ice protection sleeves described herein typically fall in the acoustic range, i.e. from about 20 to 20 000 Hz, and more particularly often fall within the smaller bandwidth of 1 to 10 kHz. Higher frequencies typically requires an increased power required to drive the actuators to a comparable amount of induced strain. It is also noted that it is also possible to make modifications to the effective de-icing mode frequencies by the configuration of the de-icing device.. For example, the effective de-icing mode frequencies may be lowered by increasing the thickness of the protection sheet.

[0039] The frequency sweep of the driving signals can be made at a slow enough rate to allow modal resonance to be activated before the frequency is swept to far away from the resonance frequency. The ideal frequency sweep rate of a particular sleeve may be determined using tuning procedures, and the sweeping bandwidth can be narrowed upon confirmation from testing.

[0040] In one embodiment having a plurality of actuators, all actuators can be activated at the same time. However, in another embodiment, the actuators can be activated sequentially to limit the peak power requirement. An example of such a sequence starts from the inboard portion of the airfoil to the other end thereof. The sequence can be an over lapping leapfrog type pattern, i.e. one actuator keeps sweeping while the one behind it is deactivated and the one ahead of it is activated. Such a sequence can be paired with the same sequence on the opposing rotor blade for balanced ice shedding. The sequential operation provides smooth de-icing progression along the blade while keeping electrical power requirements within small rotorcraft capabilities.

[0041] It should be understood that many changes may be made to the devices and methods described herein. For example, the spacing can optionnally be filled with a fluid or semi-fluid material rather than a solid or foam-like material. Also, while the embodiments described herein use piezoelectric transducers for generating mechanical vibrations in the sheet, other types of actuators may be used such as magnetostrictive actuators for example, or vibrations from other sources. The embodiments described above are intended to be exemplary only. Typically, the de-icing device can be operated in an intermittent mode in order to de-ice once a given amount of ice has accumulated. Tests have shown for instance that de-icing is more effective once a given thickness of ice has been reached. Alternately, the de-icing can be done continuously, in an anti-icing mode, to prevent ice accumulation above a given threshold, for instance. It is noted that several exemplary applications are described above and illustrated for the purpose of providing examples. It will be understood that the method or device can by applied in other contexts than the ones described specifically herein. For example, the provided methods and devices may apply to other vehicles such as unmanned aerial vehicles, ships, trains and other ground vehicles. It may also apply to buildings, infrastructures such as bridges, communication towers, wind turbines, a screen mesh, power line towers, transformer boxes, satellite dishes, and other applications such as oil platforms, drilling stations construction equipment, etc. The scope of the invention is therefore intended to be limited solely by the appended claims.

CLAIMS:

1. A de-icing device for a substructure, the de-icing device comprising : a protection sheet having a shape matching a shape of the substructure, the protection sheet being made integral to the substructure with a spacing being located between the protection sheet and the substructure, the protection sheet having an ice accumulation surface facing away from the substructure, and an underface surface facing the substructure; and at least one piezoelectric transducer positioned within the spacing and being securely bounded to the underface surface of the protection sheet, said at least one piezoelectric transducer being operable to impart vibrations at frequencies in the audible range, wherein said vibrations are of an amplitude producing a sufficient deformation in the protection sheet to remove ice accumulated thereon.

2. The de-icing device of claim 1 wherein the protection sheet is affixed to the substructure with a plurality of fasteners on at least two opposite edges of the protection sheet.

3. The de-icing device of claim 1 wherein the spacing is filled with air.

4. The de-icing device of claim 1 further comprising a vibration-permeable filler material in the spacing.

5. The de-icing device of claim 4 wherein the vibration-permeable filler material makes the protection sheet integral to the substructure.

6. The de-icing device of claim 1 wherein the vibrations are in a range of 1 to 10 kHz.

7. The de-icing device of claim 1 wherein the deformation is of above 50 μξ.

8. The de-icing device of claim 7 wherein the deformation is of above 150 μξ.

9. The de-icing device of claim 1 further comprising a frequency modulator operable for the frequency of the vibrations to sweep a given band in the audible range of frequencies.

10. The de-icing device of claim 9 wherein the bandwidth of the given band is of less than 5 kHz.

11. The de-icing device of claim 1 further comprising a controller for periodically operating the at least one piezoelectric transducer during a period of time in the order of magnitude of one second.

12. The de-icing device of claim 11 wherein there are at least two piezoelectric transducers and the controller can operate the at least two piezoelectric transducers in sequence.

13. The de-icing device of claim 12 wherein the sequence includes an overlapping period of time during which both piezoelectric transducers are in collective operation.

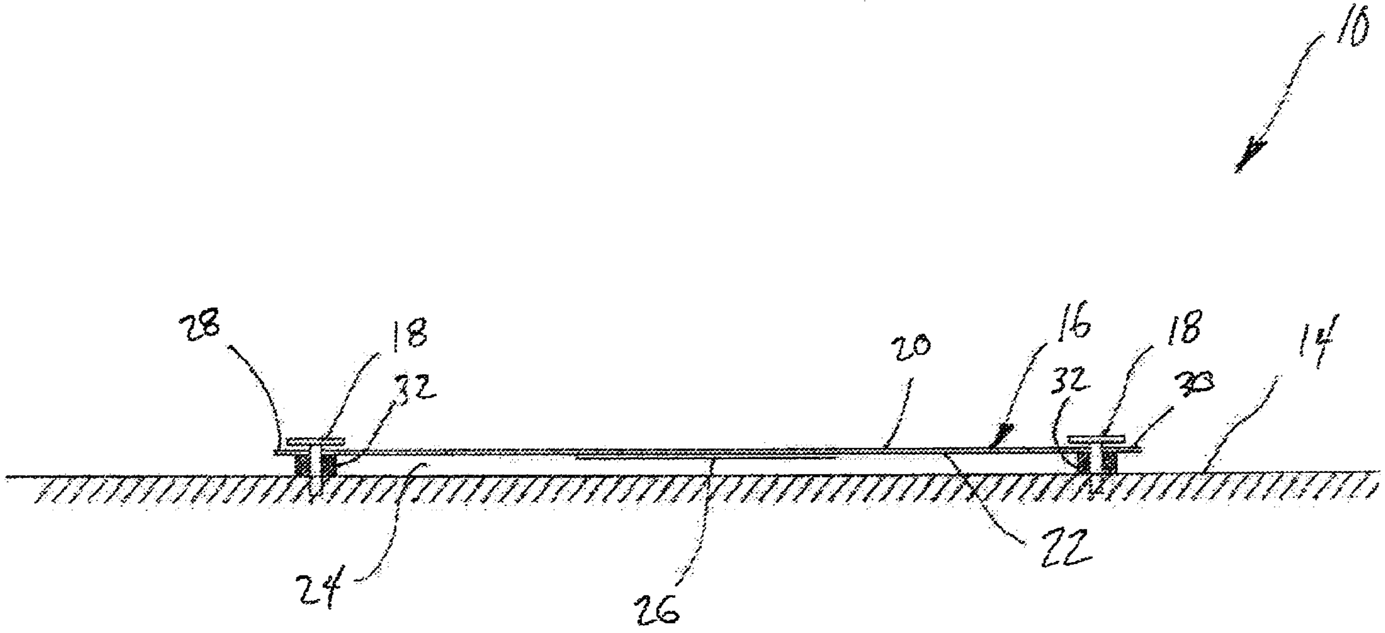

FIG. 1

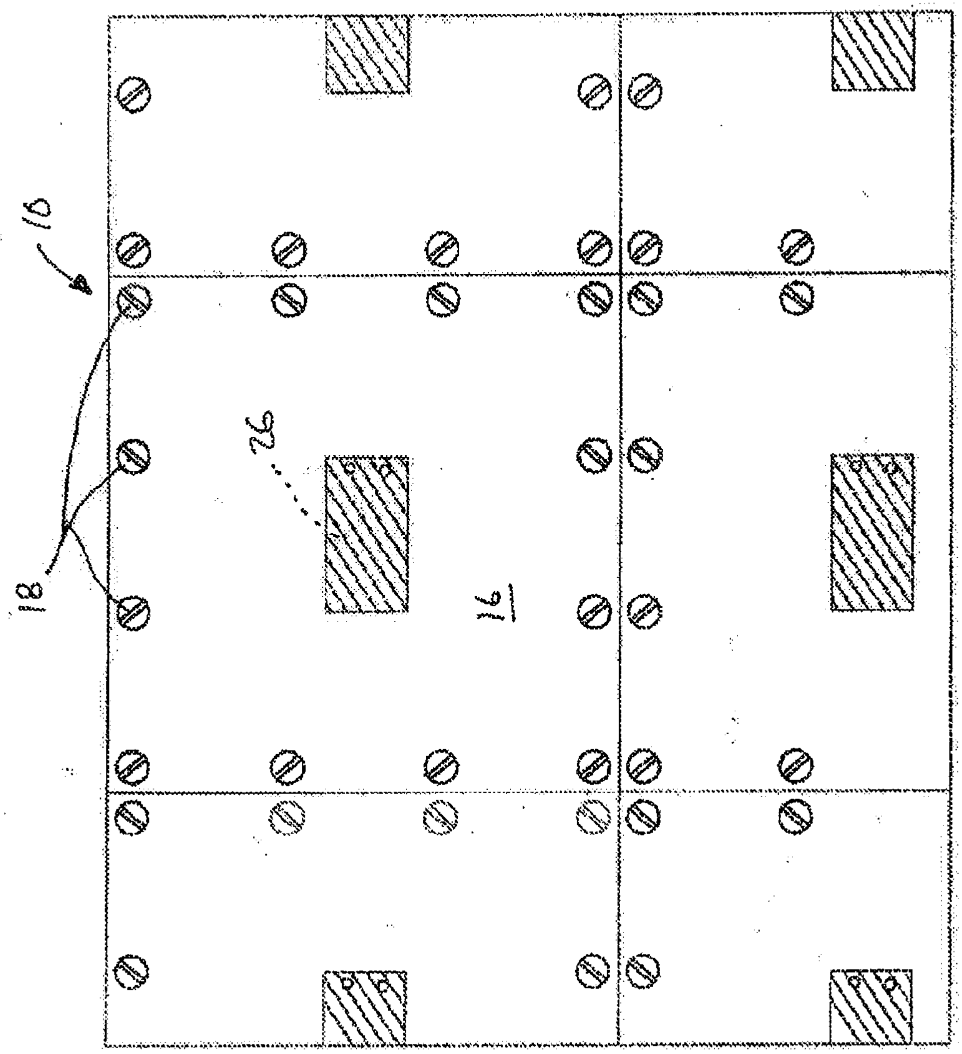

FIG.2

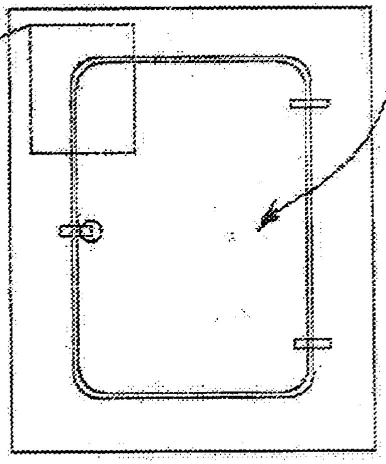

FIG. 3A

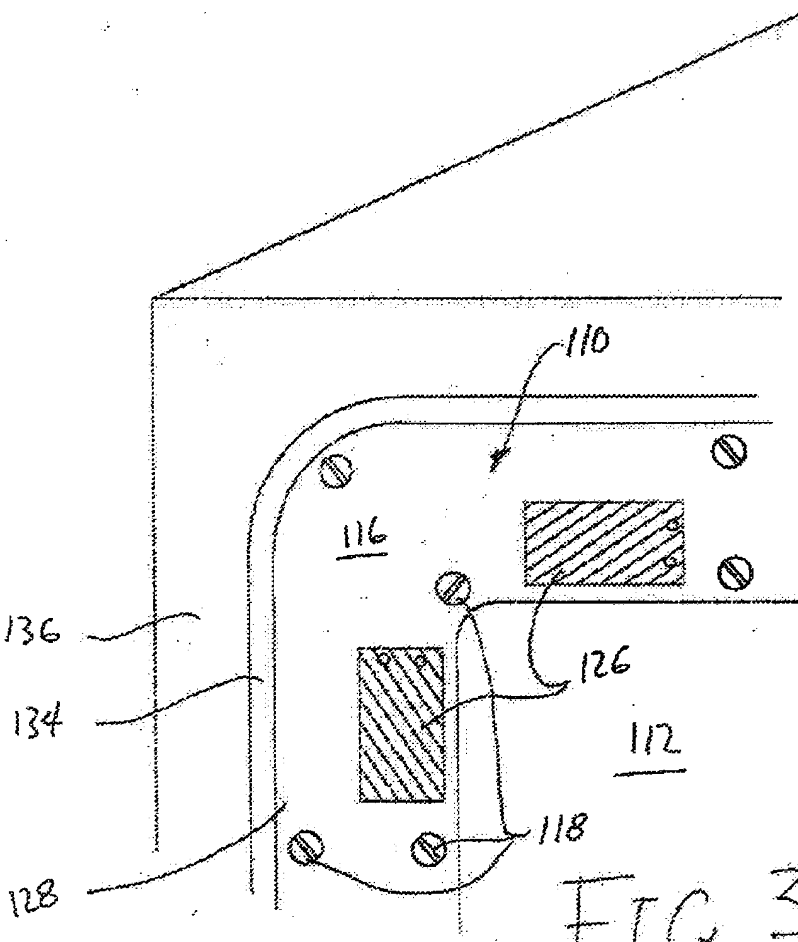

FIG. 3B

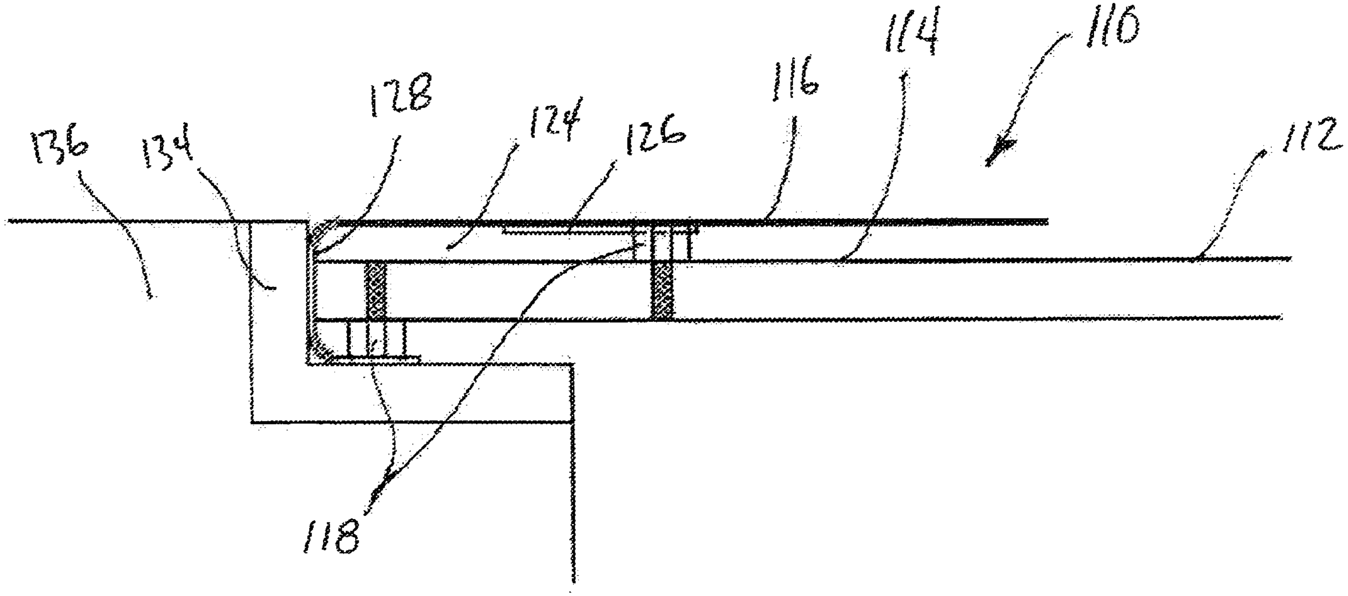

FIG. 3C

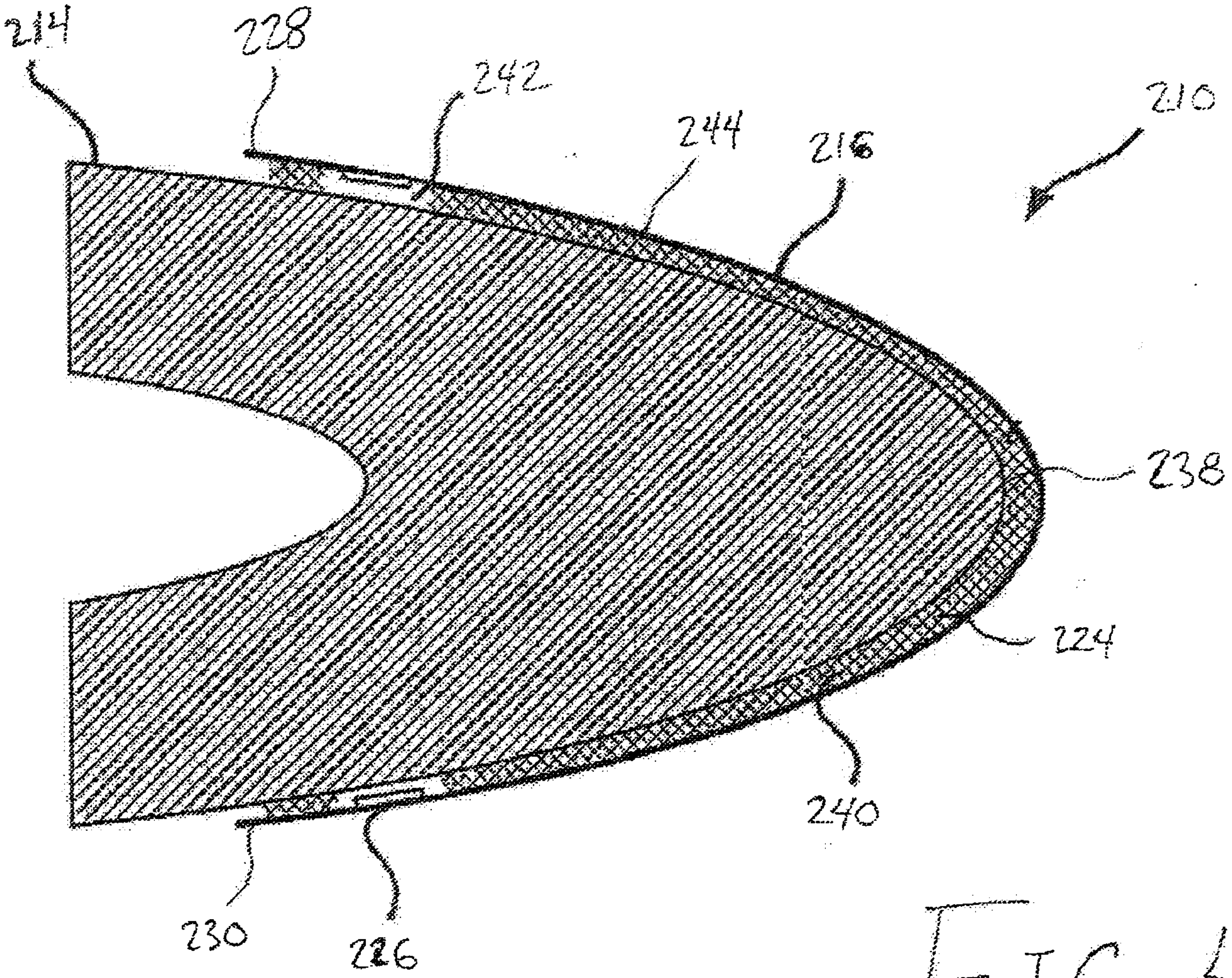

FIG. 4

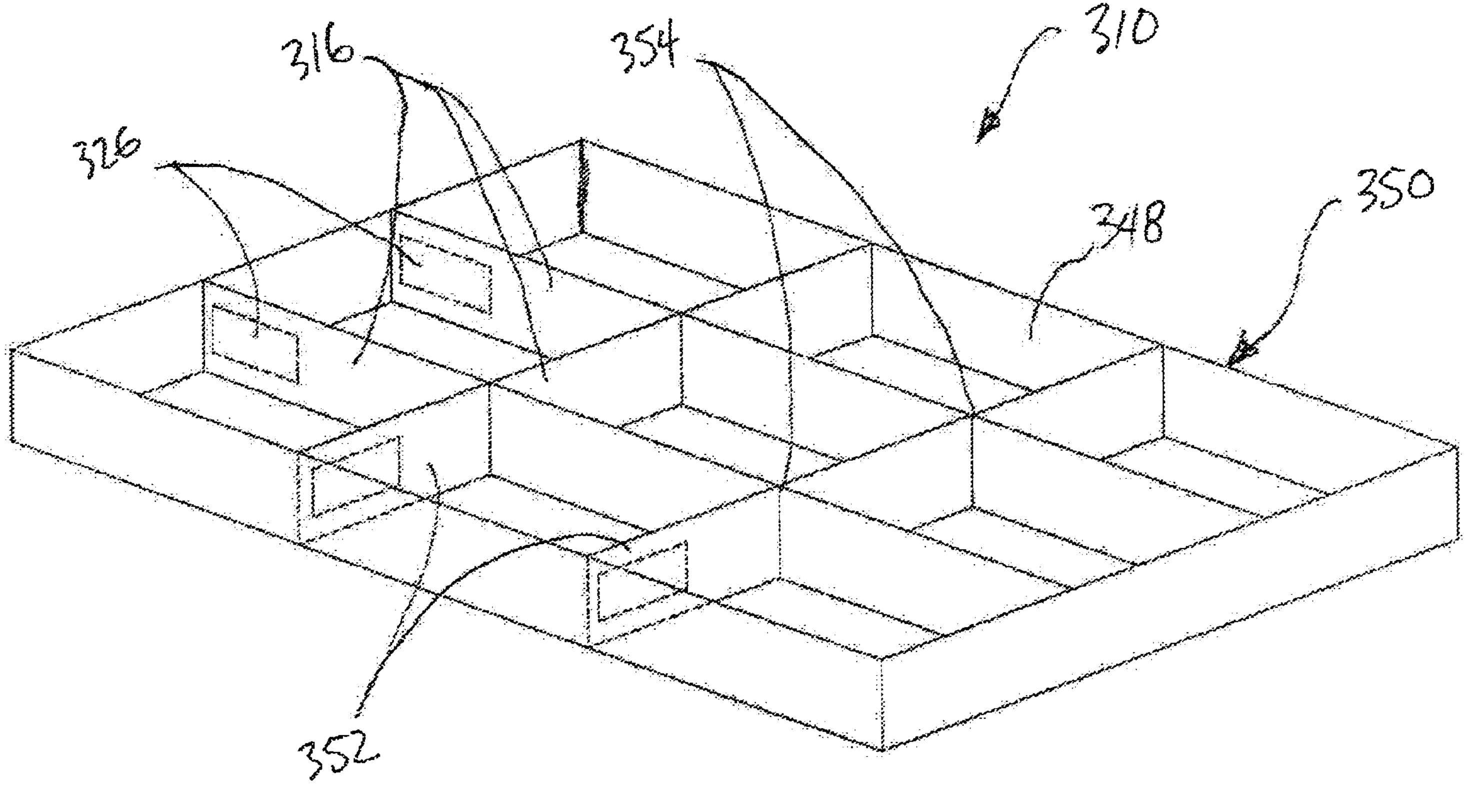

FIG.5

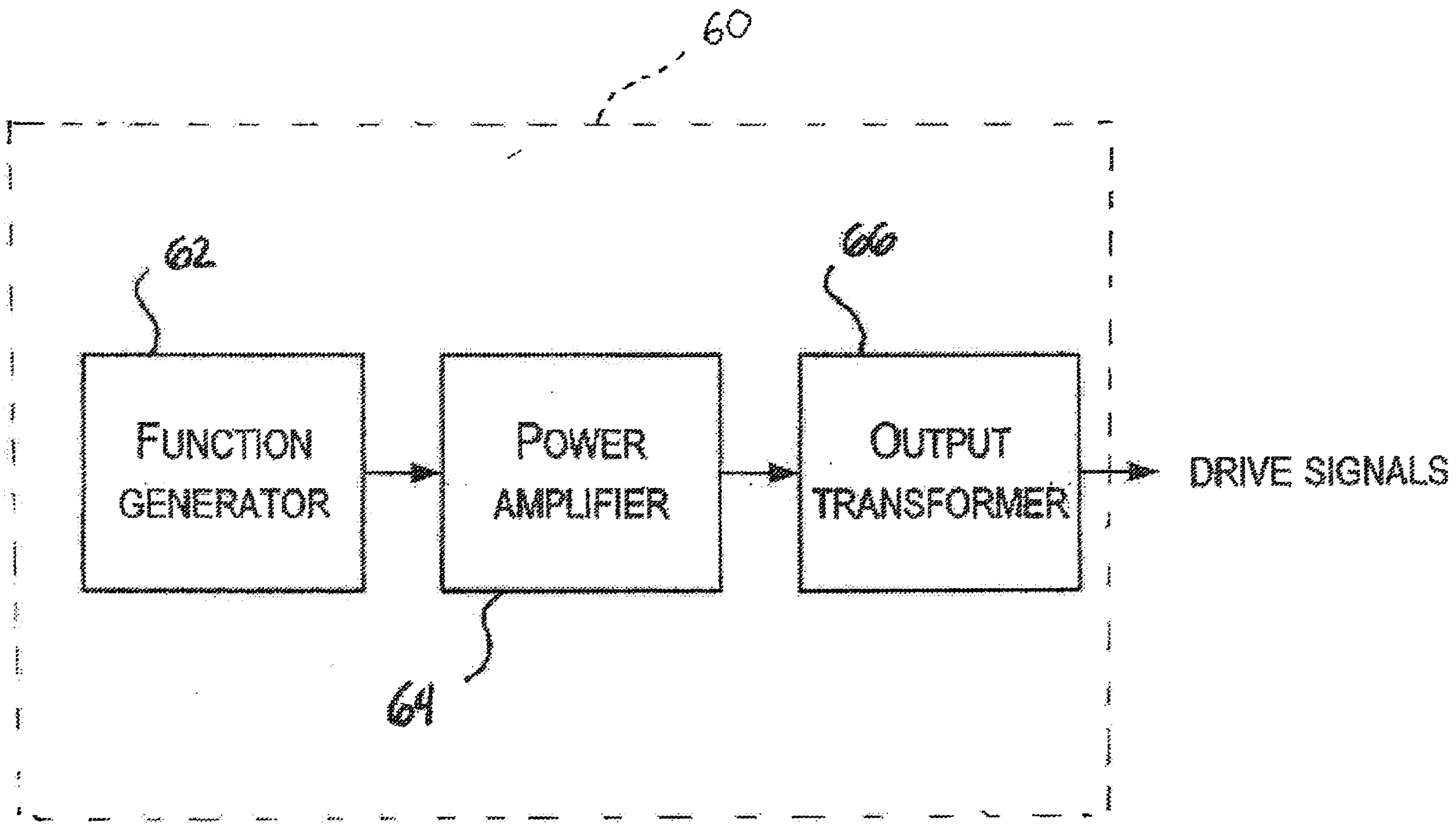
60
62
FUNCTION GENERATOR
POWER AMPLIFIER
64
66
OUTPUT TRANSFORMER
DRIVE SIGNALS

FIG. 6